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INTRODUCTION

The Institute for Computer Applications in Science and Engineering (ICASE) is operated at the Langley Research Center (LaRC) of NASA by the Universities Space Research Association (USRA) under a contract with the Center. USRA is a nonprofit consortium of major U. S. colleges and universities.

The Institute conducts unclassified basic research in applied mathematics, numerical analysis, and computer science in order to extend and improve problem-solving capabilities in science and engineering, particularly in aeronautics and space.

ICASE has a small permanent staff. Research is conducted primarily by visiting scientists from universities and from industry, who have resident appointments for limited periods of time, and by consultants. Members of NASA's research staff also may be residents at ICASE for limited periods.

The major categories of the current ICASE research program are:

- Numerical methods, with particular emphasis on the development and analysis of basic numerical algorithms;
- Control and parameter identification problems, with emphasis on effective numerical methods;
- Computational problems in engineering and the physical sciences, particularly fluid dynamics, acoustics, and structural analysis;
- Computer systems and software, especially vector and parallel computers.

ICASE reports are considered to be primarily preprints of manuscripts that have been submitted to appropriate research journals or that are to appear in conference proceedings. A list of these reports for the period April 1, 1988 through September 30, 1988 is given in the Reports and Abstracts section which follows a brief description of the research in progress.

Presently, ICASE is operated at NASA Langley Research Center, Hampton, VA, under the National Aeronautics and Space Administration, NASA Contract Nos. NAS1-18107 and NAS1-18605. In the past, support has been provided by NASA Contract Nos. NAS1-17070, NAS1-17130, NAS1-15810, NAS1-16394, NAS1-14101, and NAS1-14472.

RESEARCH IN PROGRESS

Saul Abarbanel

The method of constructing a fourth order spatially accurate scheme has been extended to the case of viscous flows (full Navier-Stokes and the various approximations to it such as thin layer equations, etc.). The stencil remains the same one used in second order schemes. The stability has been worked out for a four stage Runge-Kutta 2-D algorithm. The time step, for a cell - Reynolds number around 2-3, is the same as for the inviscid case - if the spatial accuracy is required only at steady state. If the fourth order is to be maintained also during the temporal evolution the time step is diminished by about a factor of 2 to 3 (depending on the cell Reynolds number).

Preliminary calculations (done by E. Turkel) of flow around a transonic airfoil, using the thin layer equations, indicate that most of the expected gains in efficiency are realized. Further problems will be tested in the future.

Work also continued on adopting the down-stream non-reflecting boundary condition (for viscous flows) to the case of uneven grids with local time stepping. This research is done in collaboration with Alvin Bayliss.

H. T. Banks and S. L. Keeling

In collaboration with R. Silcox (Acoustics Division, LaRC) and C. Wang (U. Southern California), we have continued our efforts on 3-D pressure field models for active noise suppression. We have formulated a typical problem as a "state-tracking" problem in optimal control for infinite dimensional state systems. A theoretical methodology based on feedback for the steady-state (periodic) case has been developed. It has been shown that the resulting feedback controls, while apparently only asymptotically optimal, are indeed optimal. Explicit operator equations for the associated Riccati gain and tracking variable have been derived and stability for the feedback system has been established.

H. T. Banks and F. Kojima

We are continuing our investigations (in collaboration with W. Winfree, M. Heath, and P. James of the Instrument Research Division, LaRC) on inverse problems arising in thermal testing of materials in space structures. Our focus for this problem is on the identification of the geometrical shape of boundaries for a thermal diffusion system with external boundary inputs. For the case where the unknown boundary shape is represented by a simple function of one variable, we were successful in developing a parameter estimation technique and the efficacy of proposed schemes was demonstrated through numerous

computational experiments. The techniques developed have now been extended to a more general version of the geometrical boundary shape using "the method of mappings." We obtain theoretical convergence results under some constraints imposed on the geometrical structures of the boundary.

H. T. Banks and I. G. Rosen

We have developed an approximation theory for the identification of nonlinear damping mechanisms in distributed parameter models for the vibration of flexible structures. In particular, our approximation theory can handle a variety of nonlinear dissipation mechanisms including ones with discontinuities. Our approach is based on the theory of monotone operators and relies heavily on the generic approximation results which we developed earlier in conjunction with our work on first order nonlinear distributed systems. In addition to a theoretical analysis we have carried out some preliminary numerical studies. The methods have been able to successfully identify a quadratic viscous damping term in a one dimensional wave equation. Further testing of our schemes is currently underway.

Alvin Bayliss

The research on spatial instabilities in supersonic flows is continuing. This work is being done in collaboration with L. Maestrello (Transonic Aerodynamics Division, LaRC) and R. Krishnan (Vigyan Research Associates, Inc.). At the present time, comparisons have been made with linear theory and experiments for a range of unstable frequencies. Nonlinear distortion has been computed for large amplitude disturbances. An ICASE report is in preparation.

A theory has been developed together with S. Abarbanel to explain the effect of local timestepping algorithms for the Navier-Stokes equations. This theory is based on a perturbation expansion of the Navier-Stokes equations and thus accounts for viscous effects. At present, this theory is being tested by studying convergence rates for a Navier-Stokes solver to see if it explains the observed rates.

Shahid Bokhari

The problem of balancing load on rings and meshes of processors using a distributed algorithm with only local information (i.e., information from neighboring processors) is being investigated. Prior work by other researchers has considered continuous, infinitely divisible load. This work focuses on the more realistic case of discrete load. It has been discovered that most of the algorithms that are applicable to the continuous load case fail for discrete loads (i.e., the final configuration of loads on processors is not optimal). An algorithm that correctly terminates in the case of rings has been developed. The

performance of this algorithm has been explored using a very large number of simulations. An analytic expression for the time required by this algorithm is being developed.

Dennis W. Brewer

Research is continuing on parameter estimation problems associated with linear evolution equations in infinite-dimensional spaces. A general algorithm based on quasi-linearization has been established along with its local convergence properties. The algorithm has been numerically tested on linear delay-differential equations. Numerical experiments indicate that the method converges rapidly when used to identify one or two unknown delays. Greater difficulties are encountered in coefficient identification because the solution may be insensitive to certain changes in the coefficients. Future research will involve continuing numerical experimentation and improving the theory to accommodate a wider class of problems.

Dennis W. Brewer and J. Steven Gibson

We are continuing our efforts to develop robust software routines for identifying parameters in robotic manipulators. The programs use numerical integration of nonlinear differential equation models and nonlinear optimization algorithms. This work is in conjunction with J. Pennington, F. Harrison, and D. Soloway (Information Systems Division, LaRC) who have provided experimental data. Our previous research indicates a need to model the integrated electro-mechanical system to reduce parameter sensitivity. We are currently developing and testing reduced models for two-link motions of the manipulator. These reduced models have the potential of providing on-line predictions to assist a teleoperator. Future research will involve the simulation of multiple-link motions and extensions of our model to manipulators with flexible joints and novel link geometries now being designed for LaRC.

John A. Burns

We are working on the development of approximating schemes for control and identification of systems governed by partial and functional differential equations. During the past six months we have concentrated on schemes that preserve and maximize controllability and observability radii under approximation. We established that the new spline based schemes developed for delay systems by Ito and Kappel preserve the basic system properties and give larger system radii than the other known schemes. We have also obtained similar results for finite element and finite difference schemes applied to heat transfer control problems.

Recently we have begun to investigate the effects of thermoelastic "damping" on control design problems involving structures. We have developed a simple simulation model for

investigating the damping due to heat loss at the boundary of an elastic body. The results seem to indicate that thermal damping is significant at low frequencies and could play an important role in feedback control design.

Richard Carter

Trust region algorithms for numerical optimization have become increasingly popular in recent years. Use of trust region modifications to Newton and Newton-like methods yield algorithms with both fast local convergence properties and robust global convergence properties.

Alternative norm trust region algorithms are being investigated for both constrained and unconstrained optimization problems. Although it is traditional to use a Euclidean or ellipsoidal norm to define the trust region, the ℓ_∞ norm seems a natural alternative if the design variables are already subject to upper and lower bounds. An optimization package has been developed to test this concept. Fumio Kojima has used this package to solve a number of numerical problems arising from system identification, and it has been highly successful. Work is currently underway to extend the package to handle more general linear and nonlinear inequality constraints via a novel choice of scaling in the trust region norm. One goal is to develop a system capable of efficiently solving problems arising from the new Control-Structures Interaction (CSI) initiative at LaRC.

Previously developed global convergence theory for algorithms using inexact function and gradient evaluations allowed either a relative error condition on gradient approximations or a condition on the angle between the approximation and the approximation error. This latter condition may have significant implications when finite difference gradients are being used, as it provides both a more direct method of testing the adequacy of a given approximation and a relatively inexpensive way of improving the approximation. These improvements have been included as an option in the aforementioned optimization package, and numerical tests are planned for the near future.

Tom Crockett

A parallel I/O package which supports disk striping for sequential file access has been implemented on Langley's Flex/32 computer. The software allows from 2 to 8 processors to be configured into a parallel I/O subsystem, with the remaining processors used for computation. Experimental results for 8-way striping showed speedups in I/O transfer rates ranging from 5 to 35. The largest speedups were obtained for the smallest block sizes, while the smallest speedups were obtained with the largest block sizes. Analysis showed that two distinct effects contributed to the speedups: (1) parallelism in the I/O system, and (2) reduced overhead for small block sizes due to buffering. For large block sizes the

limiting factor in the speedups was determined to be the data copying overhead associated with splitting records into stripes. A potential way of overcoming this limitation is to adopt a more sophisticated read-ahead/deferred-write buffering scheme. This would allow the I/O processors to operate asynchronously with respect to the calling program, thereby overlapping data movement with computation.

Some initial benchmark tests were performed on the Ardent Titan graphics computer recently installed at ICASE. Results showed up to 17 MFLOPS performance using two vector processors, although typical performance was in the range from 5 to 10 MFLOPS.

The X Window System was installed on the ICASE Sun workstation network. This provides an alternative window environment for use by the staff. Its main attraction is that it allows portable window-based applications to be developed which can be run on a variety of other systems, including the Ardent Titan. X also provides the ability for users to run computationally intensive programs on remote computers, while displaying the results on their local Sun workstation.

Naomi H. Decker

The design and analysis of robust multigrid algorithms continues to be a main focus of research. When multigrid is used to solve partial differential equations, the choices of the relaxation and the interpolation and projection can dramatically effect the convergence properties of the method. For example, in anisotropic problems with strong alignment of the operator along various directions, the relaxation must be carefully adapted to follow the behavior of the alignment. New algorithms are being developed which work equally well for these problems as well as for variable coefficient scalar elliptic equations and elliptic systems (e.g. Stokes equation).

Naomi H. Decker and David Kamowitz

Techniques for analyzing multigrid algorithms for hyperbolic problems are being developed. These techniques will lead to a firm understanding of the basic mechanism of the algorithm. For example, is there some fundamental convection of boundary information by the relaxation or does the relaxation merely damp high frequency components of the error? Understanding such basic questions should lead to the design of faster and more robust algorithms.

Naomi H. Decker and Vijay K. Naik

Recently several researchers have studied multilevel methods for robustness and for parallelizing the intra-grid and inter-grid operations. Some researchers have proposed special purpose architectures that allow one to map some important problems directly

onto the hardware and thus reduce the communication delay effects, while others have proposed new concepts that increase the robustness of the method.

Hackbusch's method, for example, eliminates the need for special relaxation and/or grid coarsening strategies in problems with strong alignments of the operator along grid lines. This method separates the error components in different frequency domains that can be eliminated efficiently in parallel. But none of these studies have conclusively shown that the optimality observed on the sequential machines is conserved in time and the number of processors needed when these methods are implemented on multiprocessors, nor is there any clear understanding about the communication, the synchronization, and the preprocessing costs involved. This is especially true when the problems considered are nonlinear with mixed boundary conditions - the type of problems that need to be solved on high performance multiprocessor systems.

Our effort is directed towards understanding the limitations of efficiently parallelizing the multigrid like concepts in solving nonlinear equations such as the Navier-Stokes equations.

Stephen Elliott

A study of the inversion of the electroacoustic response of sound reproduction systems was undertaken. Both acoustical and signal processing aspects of this problem were studied for a model enclosure. The transfer function inversion problem is formally similar to the problem of active control except that the field is being driven to some predefined state rather than zero. Results demonstrating that inversion (equalization) of the response at one observation point in an enclosure can have detrimental effects at other points will be published as an ICASE report. A more complicated, multiple observation point, formulation is introduced and shown to give improved global equalization in the model problem discussed.

The use of FIR and IIR adaptive filter algorithms was investigated as a practical implementation of the signal processing requirements of such inversion tasks.

James Geer

Work is progressing on a hybrid perturbation/Galerkin method to determine how the method might be applied to provide approximate analytical solutions to certain classes of problems involving a parameter over a wide range of parameter values. In particular, we are exploring the idea of using the method to combine information contained in perturbation expansions about several different values of the perturbation parameter. Several model problems involving regular and/or singular perturbation expansions have been studied and will be reported in a forthcoming ICASE report. In addition, we are developing the idea of

combining our method and some homotopy methods to describe fields about geometrically complicated bodies. Work on the method itself is being done with Carl Andersen of the College of William and Mary, while possible applications are being discussed with Eddie Liu (Low-Speed Aerodynamics Division) and Mike Hemsch (Transonic Aerodynamics Branch).

Investigations are also continuing concerning some fundamental properties (both from theoretical and computational points of view) of a class of "almost" singular integral equations of the first kind which are useful in representing solutions to certain elliptic exterior boundary value problems. These equations typically have the property that the domain of integration R is a proper subset of the domain of validity D of the equation. Special consideration is being given to the idea of analytically continuing the solution into the domain D . In fact, this has now been done for a large class of one dimensional integrals, such as those which occur in the representation of solutions involving a body of revolution. For this special class, a characterization of R in terms of certain properties of the analytic continuation of the kernel has been obtained, which leads to a simple numerical procedure to determine R and helps to circumvent some of the stability problems inherent in solving integral equations of the first kind. Application of the results to several two and three dimensional problems involving slender or thin bodies is being carried out.

Steve Gibson and Gary Rosen

We have been looking at control and stabilizability issues for linear thermoelastic systems. More precisely, we have been considering the question of uniform exponential stability for the standard partial differential equations of linear thermoelasticity. While we have found that it is possible to construct an appropriate Lyapunov functional for the coupled heat and wave equations together with certain boundary conditions, we have not as of yet been able to establish the uniform exponential stability of the system for other sets of boundary conditions. Preliminary numerical studies of spectra however, seem to indicate that the system is uniformly exponentially stable for all of the standard boundary conditions of physical interest. Once we have resolved the stability question, we intend to study a variety of control and associated approximation issues with particular emphasis on linear-quadratic design.

David Gottlieb

Spectral methods were applied to simulate wake flow past a circular cylinder. The compressible viscous Navier-Stokes equations were discretized by the Chebyshev Fourier pseudospectral method. The goal was to check the numerical results obtained by Rudy and Townsend using finite difference methods as well as the conflicting experiments by Sreenivasan and Van-Atta. We have demonstrated that the results are sensitive to the way

that boundary conditions are imposed. The second frequency reported by Sreenivasan can be obtained if noncharacteristic boundary conditions are used. Using boundary conditions with characteristic variables eliminate this frequency. Further studies of the effect of the Mach number on the shedding frequency are being carried out. This work is a joint effort with W. S. Don of Brown University.

We have studied the effect of quadrature formulas on the conservation properties of spectral schemes. We showed that the Clenshaw-Curtiss formula may lead to inaccuracies and loss of conservation. We developed an alternative formula based on the inner extrema of orthogonal polynomials. The new formula seems to remove the difficulty witnessed before by many researchers. This is a joint work with Craig Streett (Transonic Aerodynamics Division, LaRC).

We continue the work on spectral methods for shock wave calculations. The current effort is focused on finding a one sided filter that will enable one to achieve spectral accuracy up to the discontinuity.

Philip Hall

Work has continued on compressible stability problems. In collaboration with P. Duck, the instability of axisymmetric boundary layers on cylindrical bodies has been discussed in ICASE Report Nos. 88-10 and 88-42. It was shown that both 2- and 3-dimensional modes are possible.

The effect of shocks on hypersonic boundary layers on wedges has been studied in collaboration with S. Cowley. It was found that the presence of a shock can cause many new unstable modes to occur. Work on vortex-Tollmien-Schlichting interactions is described in ICASE Report Nos. 88-43, 88-45, and 88-46. A wide range of fully nonlinear states driven by the interactions has been described. At present, work on hypersonic instabilities in boundary layers is being carried out with particular emphasis on the role of inviscid and centrifugal modes.

Ami Harten

In the last few years, we have developed the class of ENO (Essentially Non-Oscillatory) schemes which are robust, high-order accurate methods for the numerical solution of problems with shocks. More recently, a subcell resolution technique has been devised which enables one to find the location of a discontinuity within the cell from cell-averaged data, and thus prevent the excessive smearing of contact discontinuities. Lately, the performance of the ENO schemes in one-dimensional calculations has been improved in the following ways:

1. The Godunov approach has been formulated in terms of the primitive function rather

than the conserved quantities; this allows for a more efficient organization of the time evolution algorithm and a simpler and more efficient formulation of the subcell resolution technique.

2. Using the primitive function formulation, the time-evolution by Runge-Kutta methods has been studied; this shows the relation between the original Taylor expansion of the ENO schemes and the new pointwise flux formulation of Osher and Shu (ICASE Report No. 88-24).
3. Combining primitive function values and point values of the conserved quantities, nonoscillatory schemes which use Hermite interpolation rather than the standard Lagrange interpolation have been designed.

We have also started to study the extensions of these ideas to 2D calculations. As a preliminary step to subcell resolution in 2D we have posed the following approximation problem: Given a piecewise polynomial function in 2D with a polynomial curve of discontinuity, how does one discretize so that the piecewise polynomial function can be reconstructed exactly? At this stage in the research it is quite clear that one must use line-averages.

Thorwald Herbert

Studies on bispectrum and energy-transfer methods for analyzing mode interactions in transition simulations have been studied. Computer programs for arc-length continuation to achieve global convergence in nonlinear problems have been developed.

Algorithms and numerical methods for the analysis of supersonic and hypersonic basic flows and their stability were developed. Special emphasis was on efficient single-domain and multi-domain spectral methods.

M. Y. Hussaini

Study of Mach number effects on the secondary instabilities in boundary layers is continued within the framework of both asymptotic theory and Navier-Stokes computations. Some results pertaining to the nonlinear evolution of the second mode instability of Mach 4.5 compressible boundary layer are being written up. Systematic investigation of the linear stability of compressible free shear flows is being carried out.

Time-accurate numerical simulations of finite aspect-ratio Taylor-Couette flows are continued. A specific route to chaos in three-dimensional Taylor-Couette flow with fixed end-walls has been simulated and the results are being documented. Subgrid-scale models for transitional flows are being looked into using effect direct simulation data bases.

This program of research is being carried out in collaboration with G. Erlebacher, M. G. Macaraeg, C. L. Streett, and T. A. Zang.

T. L. Jackson and C. E. Grosch

An understanding of the stability characteristics of reacting compressible mixing layers is of fundamental interest and is also extremely important in view of the projected use of the scramjet engine for the propulsion of hypersonic aircraft. In a recent report (ICASE Report No. 88-33) we presented the results of a study of the inviscid spatial stability of a parallel nonreactive compressible mixing layer.

An inviscid stability analysis is now being performed for the reactive case to determine the growth rate of a disturbance as a function of heat release due to chemical mixing and reaction. This is a critical problem in scramjet engine design since it is necessary to understand the effect of chemistry on the transition process from laminar to turbulent flows.

Mark T. Jones, Merrell L. Patrick and Robert G. Voigt

Efficient programming of parallel computers to support scientific applications is of increasing importance. Although many programming environments are available on different machines, there have been relatively few comparisons of different programming paradigms on the same machine. Several factors that contribute to the useability of a language have been identified. Using these factors we explore the strong and weak points of three parallel languages by implementing Choleski's method for solving $Ax = b$, where A is a banded symmetric positive definite matrix, on the flexible Computer Corporation Flex/32. The three languages are Concurrent FORTRAN from Flexible Computer Corporation, the Force developed by H. Jordan and PISCES developed by T. Pratt. The architecture and these languages support both shared memory and local memory implementations of the algorithm. In addition, PISCES supports message passing so in total seven programming paradigms were studied. The observations are based on the following factors: expressibility of functional parallelism and data partitioning, support for communication and synchronization, runtime cost, ease of program conversion, and user friendliness.

David Kamowitz

Work is continuing on finding heuristic guidelines for choosing stable outflow boundary conditions for nonlinear conservation laws. Certain well-known extrapolations are stable for linear problems, yet for nonlinear problems, they may result in the formulation of boundary layers or unstable reflected shocks. Preliminary results indicate that computing the speed and direction of propagation of a profile moving towards the boundary gives an

indication of the stability of the boundary conditions. In this case, the jump condition is computed not with the true flux but with the numerical flux.

Fumio Kojima

Work is continuing on the development of a parameter estimation technique for boundary value problems. Based on the output least square identification, we developed numerical schemes for estimating the boundary parameter and geometrical boundary shape of systems governed by 2-D Laplace and Poisson type equations. We have established theoretical convergence results for the proposed computational methods applying the compact regularization approach. In a joint effort with R. Carter, numerical testing is being performed using the trust region algorithm which is a powerful tool in the optimization techniques. Further research will involve applying the method developed to the inverse problem in 2-D Helmholtz equation.

Nessan Mac Giolla Mhuiris

An attracting set for a dynamical system is a region in phase space which "attracts" nearby initial conditions. Any orbit started in the neighborhood of such a set, A , will evolve towards it and not leave A thereafter. Attracting sets for dissipative systems have dimensions which are less than those of the phase space as a whole and, as they eventually trap all initial conditions, it is their character which governs the long term, asymptotic behavior of the system. Recently, examples have been found of some remarkable attractors. These *strange attractors* are characterized by the fact that orbits in them, which at some time lie infinitely close together, diverge from each other at an exponential rate and become uncorrelated in a finite time. In effect this precludes quantitative predictions of the behavior of individual orbits for all but the briefest times. Such behavior, termed sensitive dependence on initial conditions, must be present if the systems are to be considered chaotic.

Many finite dimensional flows are now known to have this sensitive dependence on initial conditions and it has been conjectured that the appearance of strange attractors are responsible for the evolution of turbulent fluid flows from their laminar precursors. A study is underway to address this conjecture. The rates at which nearby orbits diverge or converge for a given vector field is termed the Lyapunov spectrum of the flow. A strange attractor must have at least one positive and one negative Lyapunov exponent. A new method of measuring these exponents for the incompressible Navier-Stokes equations has been formulated. This method is capable of measuring both positive and negative exponents. Currently, it is being applied to the case of spatially periodic flows in both two and three dimensions. Results obtained for both cases indicate that there are indeed

chaotic attractors underlying these flows. The study is being extended to measure the *dimension* of these sets.

While a demonstration that the attractor for the Navier-Stokes dynamical system has a finite dimension is interesting, a knowledge of its numerical value does not in any sense describe that set. For example, if the dimension turned out to be 10 this does not mean that the entire flow can be captured by the first 10 Fourier modes. Significant breakthroughs in the mathematical description of turbulent behavior will only come if efficient methods are found to capture the essence of the underlying chaotic attractor. A method which shows much promise in this regard is the so-called proper orthogonal decomposition. In collaboration with L. Sirovich of Brown University, we are applying the method here to flow data obtained by numerical simulation of the Navier-Stokes equations with spatially periodic forcing. Using the proper orthogonal decomposition technique it is found that most of the energy in the flow can be captured by comparatively few modes. We shall project the full partial differential system onto these modes to obtain a low order truncation of the Navier-Stokes equations which still captures the physics to a high degree of accuracy. The low dimensional dynamical system obtained will be studied using bifurcation theory.

Dimitri Mavriplis

Work has focused primarily on the development of a full Navier-Stokes solver on unstructured and adaptive meshes capable of computing flow over arbitrarily complex geometries in two-dimensions. Research has been directed in two main areas: the generation of suitable unstructured triangular meshes with highly stretched elements in the viscous regions, and the accurate discretization and efficient solution of the Navier-Stokes equations on these meshes.

A modified Delaunay triangulation has been employed to generate unstructured triangular meshes for viscous flow calculations. In its original form, the Delaunay triangulation procedure, which has been used in previous work for inviscid flows, is a construct which produces the most equiangular triangles possible for a given set of mesh points. Thus, to obtain highly stretched triangular elements in the boundary layer regions, where the resolution required in the direction normal to the layer is much finer than that required in the tangential direction, the triangulation procedure has been modified by introducing local stretching factors throughout the domain, and triangulating in this locally stretched space. This method also has the advantage that it can be employed in conjunction with existing adaptive meshing techniques. Results of this work, including adaptive meshes about multi-element airfoil configurations, and preliminary laminar Navier-Stokes computations are the subject of a paper to be presented at the Second International Conference on Numerical Grid Generation in Computational Fluid Dynamics, at Miami Beach, Florida,

of Bokhari's linear array mapping problem is NP-complete, have developed optimizations for an exact solution procedure which is able to solve reasonably large problems, and have studied the performance of heuristics. This work is being done in collaboration with Rex Kincaid and Doug Shier (College of William and Mary) and Dana Richards (University of Virginia).

Research in reliable distributed systems has generally ignored the effect the workload mapping has on reliability. For example, software errors are more likely if two routines which share data are co-resident than if they are separated--the additional risk occurs due to unintentional synchronization errors between those tasks. This project will examine the effects that mapping can have on reliability, and will develop mapping algorithms which take both performance, and reliability into account. Other mapping issues we are considering are placement of redundant computations, and remapping after failure. This work is being done in collaboration with Phil Kearns and Steve Park (College of William and Mary).

We continue our studies of time-stepped and discrete-event simulation. Of particular interest now are mapping and dynamic remapping of nonstationary simulation models. This work is being done in collaboration with Paul Reynolds (University of Virginia).

Merrell L. Patrick

Development of algorithms for solving the generalized eigenvalue problem is continuing. An algorithm based on the Lanczos method is being implemented and tested on the Convex and Cray 2 computers. Performance of this algorithm is being compared with that of the eigensolver module in the NICE/SPAR structural analysis system running on the Cray 2. Our approach requires the development of parallel methods for solving indefinite linear systems of equations. Such systems might arise because shifting is required to improve convergence rates. A good shifting strategy is also required for optimal performance of the algorithm. The algorithm will also be implemented using the Force language due to Harry Jordan and it's performance compared to that of the non-Force version. This work is being done in collaboration with Mark Jones, a Ph.D. student at Duke University, and Olaf Storaasli (Structures and Dynamics Division, LaRC).

Work is continuing with Vijay Naik on the study of load distribution schemes which minimize the total data traffic required in Cholesky factorization of dense and sparse, symmetric, positive matrices on multiprocessor systems with local and shared memory. The study has been extended to a more general class of computations represented by certain directed acyclic graphs.

A new effort is commencing with Peter Gnoffo (Space Systems Division, LaRC) which will study the impact of chaotic relaxation on the performance of an upwind relaxation

algorithm which simulates hypersonic, nonequilibrium flow about blunt bodies.

Doug Peterson

The recent file server upgrade from a 3/180 to a 3/280 cpu proved to be a performance handicap. This is largely due to two factors; the writeback cache and the ethernet collision rate. The writeback cache induces a performance penalty if the hit rate is near zero, which reduces overall performance. In a heavily loaded server, the cache hit rate is low because data shuffled between the network and disk is seldom seen by the cpu more than once. The ethernet collision rate was typically a factor of 3 to 4 times higher with the 3/280 cpu than with the 3/180, thus reducing file server response. Consequently, the cpu upgrade has been rejected. To properly support the number of diskless workstation at ICASE and to provide much needed disk space, an additional 3/180 file server has been ordered.

ICASE is now registered with SRI-NIC as the domain ICASE.EDU, and has its own Class C network, 192.42.142. ICASE continues to participate in the development and operation of a center-wide TCP/IP network at Langley, with its Sun computer network playing a key role. ICASE has provided technical support through consultation in all aspects of UNIX including network design, management issues, communications protocols, IP internet addressing, establishment of reliable electronic mail, user training, and system administration.

ICASE is participating in the development of extensions to the IEEE 1003.1 Trial-Use POSIX standard concerning supercomputers. To date, this participation has included attendance at /usr/group committee meetings, briefings of Langley Management, and recommendations for additional Langley participation.

Terrence W. Pratt

The PISCES 2 parallel programming environment is being ported to a 32-node Intel iPSC/2 hypercube at the University of Virginia. This is the same system that is currently installed on the NASA Langley FLEX/32. The effort to implement a parallel version of the NASA NICESPAR testbed will be directed toward the hypercube once the PISCES system is operational on that machine.

New research has begun into the problem of the organization and management of parallel I/O in distributed and shared memory parallel computers. The research goal is to understand how best to organize the movement of data through a high-performance parallel computer, where the system has multiple disk units accessible from the nodes of the machine in parallel. This research will use the general framework of the PISCES system to experiment with new language features to allow the applications programmer to effectively manage parallel I/O operations.

exchange for minimizing hardware interlocks. A definition for the communication hardware has been completed. Work begins on the definition of the states and operations of the virtual and physical processors; in particular, emphasis is placed on trying to create a design in which various portions might be built with SIMD forms.

To support the Navier-Stokes Computer visual programming environment, mechanisms were developed for verifying correctness of delays in the ALU pipelines and for deriving such information from high-level array references and loop definitions. A generalized form of the version described in the interim report is being developed.

Vijay K. Naik

Research is continuing towards developing a methodology for analyzing the effects of data dependency patterns, found in a general class of algorithms, on the communication and synchronization requirements for asynchronous multiprocessor systems. Under this methodology, relationships are established between the extractable parallelism and the necessary communication and synchronization requirements of an algorithm. These relationships quantify the tradeoffs between the computation time and the data traffic associated with an algorithm. They also enable a systematic study of the performance of the algorithm independent of the characteristics of the underlying architecture. As a consequence of this, it is possible to select partitioning and assignment schemes which result in the minimum total execution time and use an optimum number of processors.

The class of algorithms analyzed so far are those with the dependency graphs in the form of a regular square grid, a generic rectangular grid, and three and higher dimensional cubes. In all the cases, each vertex is associated with a constant number of dependency arcs. The cases of factoring dense and sparse matrices are considered as the examples of the algorithms with varying dependencies at the vertices.

David Nicol

Two model problems, a one dimensional fluids algorithm using dynamic regridding, and a battlefield simulation have been implemented on the FLEX/32 for the purpose of studying dynamic load balancing policies. These codes serve as testbeds for (1) centralized, static "risk averting" policies, (2) dynamic scheduling of risk averting policies, (3) dynamic remapping of exact balance policies, (4) decentralized balancing policies. This work is being done in collaboration with Joel Saltz and Jim Townsend (High-Speed Aerodynamics Division, LaRC).

Irregular and dynamic scientific problems are difficult to map onto parallel processors optimally. Another line of research explores our ability to find polynomial-time mapping algorithms for constrained problem classes. We have shown that a multi-stage extension

December 1988.

The accuracy of the Navier-Stokes solver has been investigated by examining various formulations of the artificial dissipation and boundary conditions on regular triangular meshes for a simple flat plate boundary layer, as well as for laminar flow past a single airfoil. The efficiency of the solver has been enhanced by the incorporation of an unstructured multigrid algorithm coupled with an adaptive meshing technique. The results of this work will be presented at the 27th AIAA Aerospace Sciences Meeting in Reno, Nevada, January 1989.

Piyush Mehrotra and John Van Rosendale

The main focus of our research has been the design and implementation of BLAZE\2, a parallel object oriented language. During the last six months we have concentrated on the issue of specification and control of concurrency within BLAZE\2 objects. Most object-oriented languages use a monitor like approach to data structures, allowing only one thread to access the structure at any time. In BLAZE\2, we have designed a set of constructs which allow multiple processes to concurrently access a shared data object in a safe and deadlock free manner.

We have also investigated the issue of managing multiple threads of control flow in the run-time environment. Given the explicit process semantics of BLAZE\2, and user specified locks, process suspension and resumption is likely to be a common operation, and the overhead involved is clearly critical. We designed an extension of C which provides support for extremely lightweight threads of control flow to reduce the overheads associated with heavyweight processes. The main goal here is to provide a high-level portable target virtual machine for the BLAZE\2 compiler.

David Middleton

Several aspects of fine-grained parallelism are being studied. In the SIMD arena, this involves alternative hardware implementations for nested 'if' statements and, with Sherry Tomboulion, evaluating local addressing abilities for SIMD processing elements.

Study continues on the virtual machine concept as presented by the FFP machine. The speed, flexibility and variable granularity displayed by the hardware partitioning process provide several opportunities for novel approaches to finding massive parallelism. An implementation of the RETE matching algorithm used in the OPS language and presented at the Canadian AI conference will be simulated in terms of such virtual machines. Other applications include methods for performing sparse matrix computations exploiting associative processing.

A minimal FFP Machine is being defined, that is, one in which pipelining is discarded in

Peter Protzel

Together with D. Palumbo (Information Systems Division, LaRC) we continue our efforts to study the possible application of Artificial Neural Networks (ANNs) in the area of Reliable Computing. Specifically, we are looking at the problem of dynamically reconfiguring the interconnection network of a fault-tolerant multi-processor system. This reconfiguration becomes necessary in the event of a component failure and interrupts all computations during the reconfiguration time. The reconfiguration itself is a constrained optimization problem with multiple solutions depending on the architecture of the network and on the number of available spare links and nodes. The reconfiguration time is critical for certain real-time systems, e.g. fly-by-wire aircraft control systems, and it essentially determines the reliability of the overall system. Therefore, it is important to have a very fast, very reliable mechanism that controls the reconfiguration in an optimal way.

There is a certain class of 'programmable' ANNs that seems to be well suited for this particular application and that has been successfully used to solve hard optimization problems like the Traveling Salesman Problem. The attraction of ANNs results from their adaptability, their inherent fault-tolerance, and their extreme speed when implemented in hardware. However, there is still a number of problems associated with the practical use of ANNs; for example, their behavior is non-deterministic and their performance characteristics are statistical values. Furthermore, there are no general guidelines on how to 'program' an ANN to perform a given task and how to find the best suitable problem representation, which determines the ANN architecture. We are currently investigating those issues by simulating ANNs for several model problems and we are trying to quantify the fault-tolerance by deliberately injecting faults and observing the resulting performance.

Joel H. Saltz

In collaboration with Ravi Mirchandaney, we extend the class of problems that can be effectively compiled by parallelizing compilers. This is accomplished with the `doconsider` construct which would allow these compilers to parallelize many problems in which substantial loop-level parallelism is available but cannot be detected by standard compile-time analysis. We describe and experimentally analyze mechanisms used to parallelize the work required for these types of loops. In each of these methods, a new loop structure is produced by modifying the loop to be parallelized. We also present the rules by which these loop transformations may be automated in order that they be included in language compilers. The main application area of our research involves problems in scientific computations and engineering. The workload used in our experiments includes a mixture of real problems as well as synthetically generated inputs. From our extensive tests on the Encore Multimax/320, we have reached the conclusion that for the types of workloads we

have investigated, self-execution almost always performs better than pre-scheduling. Further, the improvement in performance that accrues as a result of global topological sorting of indices as opposed to the less expensive local sorting, is not very significant in the case of self-execution. The results of this work will appear as an upcoming ICASE report.

Joel H. Saltz and David Nicol

Many problems are characterized by a high degree of potential data level parallelism. In many cases, workloads cannot be fully characterized during compilation due to data dependencies that become manifest only at runtime. In these cases, we must utilize methods applied during the program's execution to parallelize the work specified by the program. We are designing and implementing an automated runtime system, designed to be interfaced to high level languages. The system seeks to efficiently parallelize, cluster, or aggregate and math workloads from scientific computations.

Three basic runtime aggregation strategies are currently being pursued. When the user desires, we allow the specification of an explicit high level strategy. We are also developing a variety of runtime aggregation strategies. Some of these make implicit use of the substantial degree of regularity often present in many problems. Others do not depend on the existence of any particular pattern of data dependencies. All of these strategies are generally parameterized so that the granularity can be specified in a straightforward, machine independent manner.

Experimental work to characterize aggregation strategies has been performed on the Encore Multimax, the FLEX/32, the Intel iPSC/2, and the CM-2.

The problems examined were quite realistic. We utilized a sparse matrix Krylov space solver preconditioned with incompletely factored matrices, a time driven discrete event simulation, a fluid dynamics simulation code employing an adaptive mesh, codes that parallelized the solution to very sparse triangular systems of linear equations along with programs that examined dynamic programming based string matching algorithms. Methods of obtaining parameterized tradeoffs between load balance and the costs of synchronization and/or communication were proposed and tested, and methods of scheduling problem mappings were investigated. Some of this work had been reported in ICASE Reports 87-22, 87-39, and 87-52. New results are reported in an updated version of ICASE report 87-52 submitted to Journal of Parallel and Distributed Computing; an updated version of the material in 87-22 has been accepted for publication in SISSC. We are now in the process of generalizing these aggregation and scheduling methods.

We are also in the process of defining and constructing a C based intermediate language to be used between the compilers and the runtime system. This intermediate language is also being designed to be usable in a stand-alone manner.

A directed acyclic graph describing the parallelism available is generated when the program is executed, and the contents of the partition tuples are decided using generalized versions of the aggregation strategies described above. An ICASE report describing this work is being prepared.

Paul Saylor

Linear systems arise in a feedback control strategy for nonlinear aerodynamical systems operating at a high angle of attack. It is proposed to employ an iterative method for the efficient solution of these systems. A rough sketch of the algorithm suggests that an iterative method, used with a preconditioner could solve the linear equations in one third the time required for the direct method (computing the LU -decomposition.)

The control problem matrices are time dependent,

$$\mathbf{A}^{(k)}\mathbf{x}^{(k)} = \mathbf{b}^{(k)}$$

where k denotes the k th time step. The usual method of solution is to compute the LU -decomposition of each $\mathbf{A}^{(k)}$ and then use it to solve for $\mathbf{x}^{(k)}$. The advantages of iterative methods are less storage and the promise of faster execution. However, faster execution is not guaranteed and usually requires preconditioning.

A preconditioner based on the LU -decomposition for the first of these matrices would yield an effective preconditioner for several time steps. The work for an iterative method is (i) the start-up work to compute the LU -decomposition; (ii) the work for each step of the iteration, which includes a forward solve and a back solve. This is the basis for comparing work for the preconditioned iterative method to that required for the LU -decomposition.

Efficient iterative methods usually require a set of parameters. An incomplete conjugate gradient style iteration requires computing a set at each time step, which is not desirable. An adaptive Chebyshev method could be designed to compute the parameters once, then update these only when necessary. Another iterative method to consider is Richardson's method, which has some advantages in flexibility compared to the (second order) Chebyshev iteration. For example, the matrix operations could be "chained" more easily with Richardson's method than with the Chebyshev method.

Jeffrey S. Scroggs

Current research is in the area of the development of new numerical algorithms guided by asymptotic analysis. The analysis brings more of the physics into the formulation of the algorithm. The result is an algorithm which is both more efficient and more accurate. An example of this class of algorithms follows.

A domain decomposition algorithm suitable for transonic flow is being explored. Asymptotic analysis is exploited to dictate the subdomain boundaries and identify physically motivated parallelism. The algorithm has been demonstrated on a one-dimensional scalar equation. The method involves a functional iteration, and most recently, the algorithm has been shown to converge to shocks which satisfy an entropy condition. Even though the experiments allow the subdomains to change, current convergence proofs assume that the subdomains are the same from iteration to iteration. This is an area of current research.

The algorithm has been generalized for systems of equations in multiple dimensions. Currently underway is the implementation of the multidimensional algorithm on several machines which represent the state-of-the-art in parallel computers. Initially, a machine-independent implementation suitable for the Ardent Titan, Connection Machine 2, and Alliant FX/80 is planned. This portion is in the preliminary stages.

Sharon Seddougui

The hydrodynamic instability of compressible boundary layers is being investigated by using asymptotic methods for large Reynolds numbers. In particular, we have considered the stability of the three-dimensional compressible boundary layer due to a rotating disc. We confine our attention to the lower-branch stationary viscous modes. These are cross-flow instabilities which occur, for example, on swept back wings and turbine blades. These modes were first described by P. Hall (ICASE Report No. 85-40) for an incompressible flow. He showed that for large Reynolds numbers these modes have a triple-deck structure. It was found that for a compressible boundary layer these modes only exist below a critical supersonic Mach number. A weakly nonlinear investigation was carried out to obtain asymptotic solutions which describe the structure of the wavenumber and the orientation of these modes as functions of the local Mach number. Results were obtained for a thermally insulated disc as well as for a disc maintained at a constant temperature. The nonlinear effects enable the finite amplitude growth of a disturbance close to the neutral location to be described. The results are similar to those for an incompressible flow; namely, there exists a threshold amplitude of the disturbances below which oscillations decay to zero and above which they grow in amplitude as the distance from the position of neutral stability is increased. This work is in the process of being prepared for an ICASE Report.

The effect of significantly cooling the wall temperature on the compressible triple-deck structure for three-dimensional disturbances is jointly being investigated with Frank Smith. A new flow structure has been found, and the results will be important in the study of the instability of hypersonic boundary layers.

Charles Speziale

A variety of recently developed second-order closure models (including those of Shih-Lumley and Launder and co-workers) were tested in collaboration with T. B. Gatski (High-Speed Aerodynamics Branch, LaRC) for the problem of homogeneous turbulent shear flow in a rotating frame. It was found that the newer models do not yield significantly improved prediction over the older second-order closure models. Scaling laws for homogeneous turbulent shear flows in a rotating frame were developed in collaboration with Nossan Mac Giolla Mhuiris. The commonly assumed Richardson number scaling was shown not to be a rigorous consequence of the Navier-Stokes equations; it only applies to low-order second-moment truncations of the Navier-Stokes equations.

Work on the development of subgrid scale models for the numerical simulation of the transition to turbulence was begun in collaboration with Ugo Piomelli (University of Maryland), T. A. Zang (High-Speed Aerodynamics Branch, LaRC) and M. Y. Hussaini. Groundwork was also laid for the development of compressible second-order closure models for use in the National Aerospace Plane Project.

Shlomo Ta'asan

Research is being conducted on developing multigrid methods for identification problems and bifurcation related problems. In the first subject the focus is on identification problems governed by elliptic partial differential equations, with boundary observations. Unknown coefficients appearing in the differential equation are to be estimated from the observed data. The attempt is to develop an approach in which the regularization for the problem is part of the solution process and is done adaptively. Basic processes in the multigrid such as the relaxation will incorporate a regularization, by rejecting changes in the coefficients that introduce negligible changes on the boundary measurements. Based on the above, an adaptive discretization for the coefficients and probably also for the solution will be used.

In the other area there is an attempt to apply a method developed recently for stability calculations to incompressible flow problems. Flow in a channel is used as a model. The problem is to calculate the Reynolds number for which stability occurs. The interesting feature of the method is that the critical point is solved for directly, using an appropriate FAS multigrid solver. Calculating critical Reynolds numbers as a function of another parameter (for example, the velocity of the top plate) will be demonstrated next.

Eitan Tadmor

We continue the development of the Spectral Viscosity (SV) method introduced in ICASE Report No. 87-54. Convergence was proved in ICASE Reports No. 88-4 and

88-41 for scalar and some 2 by 2 systems of conservation laws. Currently, we investigate spectral viscosity parameterizations which guarantee the non-oscillatory behavior of the numerical solution and augment it with post-processing techniques in order to recover the exact solution with high accuracy in regions of smoothness. Extensions to the non-periodic case (Chebyshev) are also sought. The question of local convergence rate is studied for both the SV method as well as the modern non-oscillatory.

Finally, we continue to study the non-oscillatory central difference method proposed in ICASE Report No. 88-51, extending it to multidimensional problems, comparing characteristic vs. component-wise reconstruction, and proving the large time behavior along the lines of ICASE Report No. 83-15.

Hillel Tal-Ezer

The numerical scheme which simulates the heat transfer in a thin plate ($\Delta z \ll \Delta x, \Delta y$) results in a very stiff system of ordinary differential equations,

$$U_t = AU$$

where A is an $N \times N$ matrix. The domain D which contains the eigenvalues of A is

$$D = \{x | x \in [a_1, b_1] \cup [a_2, b_2], a_1 < b_1 \ll a_2 < b_2 < 0\}.$$

A standard explicit scheme does not take advantage of the fact that there are no eigenvalues in $[b_1, a_2]$. Thus, one should choose a very small time step $\Delta t (\sim \Delta z^2)$ to march the solution in time. In the present research we describe an algorithm which does not take into account the special shape of the domain D . It is based on polynomial approximation of the evolution operator $\exp(tA)$. The efficiency of the algorithm can be traced to the fact that the construction of the polynomial is based on interpolating the function $\exp(tz)$ in the two intervals containing the eigenvalues, without "wasting energy" on the huge gap between them.

Sherryl Tomboulia

Good results on a spectral method code for solving the Navier-Stokes equations for incompressible flow on the Connection Machine 2 have been obtained in collaboration with Craig Streett (Transonic Aerodynamics Division, LaRC) and Michele Macaraeg (High-Speed Aerodynamics Division, LaRC). The basic method was presented at the Scientific Applications on the Connection Machine meeting, held at the Ames Research Center in September. Results for flow in a channel will be presented at the Supercomputing 88 conference in November. The algorithm run on a 16K CM2 is competitive with the Cray2

for problems of size (128 x 128 x 101), and we estimate that the code will be significantly faster than the Cray for problems of size (256 x 256 x 101) using 64K CM2.

Work is continuing on methods for graph embedding and communication in SIMD architectures. A presentation on this work was given at the Frontiers of Parallel Processing Conference held at George Mason University.

We explored the possibility of using neural networks for robot motion control. Particularly, we examined using Kanerva's Sparse Distributed Memory Model to control the angular velocities of the robot arm when given input from a joystick. Research has been suspended because the computational requirements of this method for real-time 3-D control exceed the capability of the computers currently interfaced with the robots.

Research on extensions to SIMD computing is continuing in collaboration with David Middleton. We are establishing computational models that can be used when SIMD computers have local indirect addressing. Exploration on numerical applications using this technique are to be done with John Van Rosendale and David Nicol.

Investigation of using cellular automaton methods for reactive chemistry is being done with Harry Berryman, a graduate student at Yale. We are planning to do a comparison of two varieties of cellular automaton models with the solution of the PDEs that describe the reaction. This direct comparison should provide useful information as to the validity of cellular automaton methods for this type of problem.

Eli Turkel

As indicated in previous reports the major difficulty with central difference schemes for fluid dynamics is the implementation of the artificial viscosity. This viscosity consists of two parts. One part behaves like a second order difference and is used to enforce an entropy-like condition at shocks. The other portion of the artificial viscosity is a fourth difference which suppresses even-odd oscillations and allows the code to converge to a steady state. This is especially important when multigrid is used to accelerate the convergence to a steady state. In one ICASE report a selection of three dimensional inviscid cases were run. A large variety of wings were selected including delta wings and cranked wing shapes. The Mach numbers ranged from 0.5 to 2.5. In all cases the multigrid code obtained a reduction of at least 5 orders of magnitude in the density residual after 100 iterations. In some cases the residual was reduced by 10 orders of magnitude. The difficulty is that the results depend strongly on the coefficients of the artificial viscosity; in particular, increasing the viscosity increases the convergence rate but at the expense of smearing the shocks and changing the lift and drag. Thus one has the choice of fast but less accurate solutions or slower but more accurate solutions. However, even the slower convergence was still reasonable. Also the convergence rate achieved with the cell-centered scheme is similar to that achieved with a

cell-vertex scheme.

In a second ICASE report the artificial viscosity was examined in more detail. In particular using an upwind scheme with characteristic decomposition is similar to introducing a matrix viscosity. Based on this analogy, a matrix viscosity was introduced into the central difference scheme. This dramatically improved the accuracy of the code in some difficult cases but at the expense of additional computer time.

Also, a new project was begun to look at the effect of defect correction on the convergence rate of the scheme. This defect convergence was based on the observation that the scheme converges extremely fast when a low order artificial viscosity is used. Thus, we try to get the convergence rate of the first order artificial viscosity but correct to gain second order accuracy. Preliminary runs do not show any improvement in the total convergence rate but additional work is continuing.

Bram van Leer

Continued efforts to represent oblique waves in the approximate Riemann solver on which numerical flux functions for the Euler equations are based, have led to a theoretically appealing algorithm (work in collaboration with P. L. Roe). The algorithm explains finite differences between the state quantities of neighboring two-dimensional cells by a combination of one acoustic wave, one wave that is either an acoustic or a shear wave, and entropy wave. This model overcomes previous problems, which resulted from trying to use a single, most representative wave, by least-squares fitting to the data. That led to a sudden switch of the interpretation of the data, from an acoustic wave to a shear wave, with an accompanying 90-degree jump in its propagation direction. The new algorithm is continuous. It remains to be tested in practice.

Other areas explored with P. L. Roe were: analytic preconditioning of the Euler equations, in particular, by assuming constant total enthalpy, and the effect it has on the formulas of Roe's approximate Riemann solver; explanation of pressure disturbances, found by V. Venkatakrishnan (Analytical Services and Materials, Inc.) in numerical results containing an oblique shear wave, as a consequence of the incorrect one-dimensional wave decomposition used in the Riemann solver; and limiting of gradient values for MUSCL-type schemes on triangular grids.

REPORTS AND ABSTRACTS

Shu, Chi-Wang and Stanley Osher: *Efficient implementation of essentially non-oscillatory shock capturing schemes, II*. ICASE Report No. 88-24, April 18, 1988, 62 pages. Submitted to J. Comp. Phys.

In this paper, we extend our earlier work on the efficient implementation of ENO (essentially non-oscillatory) shock capturing schemes. We provide a new simplified expression for the ENO construction procedure based again on numerical fluxes rather than cell-averages. We also consider two improvements which we label ENO-LLF (local Lax-Friedrichs) and ENO-Roe, which yield sharper shock transitions, improved overall accuracy, and for lower computational cost than previous implementation of the ENO schemes. Two methods of sharpening contact discontinuities—the subcell resolution idea of Harten and the artificial compression idea of Yang, which those authors originally used in the cell average framework—are supplied to the current ENO schemes using numerical fluxes and TVD Runge-Kutta time discretizations. The implementation for nonlinear systems and multi-dimensions is given. Finally, many numerical examples, including a compressible shock turbulence interaction flow calculation, are presented.

Murphy, K. A.: *Estimation of time- and state-dependent delays and other parameters in functional differential equations*. ICASE Report No. 88-25, April 26, 1988, 51 pages. Submitted to SIAM J. Applied Math.

We develop a parameter estimation algorithm which can be used to estimate unknown time- or state-dependent delays and other parameters (e.g., initial condition) appearing within a nonlinear nonautonomous functional differential equation. The original infinite dimensional differential equation is approximated using linear splines, which are allowed to move with the variable delay. The variable delays are approximated using linear splines as well. The approximation scheme produces a system of ordinary differential equations with nice computational properties. The unknown parameters are estimated within the approximating systems by minimizing a least-squares fit-to-data criterion. We prove convergence theorems for time-dependent delays and state-dependent delays within two classes, which say essentially that fitting the data by using approximations will, in the limit, provide a fit to the data using the original system. We present numerical test examples which illustrate the method for all types of delay.

Banks, H. T., Simeon Reich, and I. G. Rosen: *An approximation theory for the identification of nonlinear distributed parameter systems*. ICASE Report No. 88-26, April 26, 1988, 37 pages. Submitted to SIAM J. Control.

An abstract approximation framework for the identification of nonlinear distributed parameter systems is developed. Inverse problems for nonlinear systems governed by strongly maximal monotone operators (satisfying a mild continuous dependence condition with respect to the unknown parameters to be identified) are treated. Convergence of Galerkin

approximations and the corresponding solutions of finite dimensional approximating identification problems to a solution of the original infinite dimensional identification problem is demonstrated using the theory of nonlinear evolution systems and a nonlinear analog of the Trotter-Kato approximation result for semigroups of bounded linear operators. The nonlinear theory developed here is shown to subsume an existing linear theory as a special case. It is also shown to be applicable to a broad class of nonlinear elliptic operators and the corresponding nonlinear parabolic partial differential equations to which they lead. An application of the theory to a quasilinear model for heat conduction or mass transfer is discussed.

Speziale, Charles G. and Nessim Mac Giolla Mhuiris: *On the prediction of equilibrium states in homogeneous turbulence*. ICASE Report No. 88-27, April 26, 1988, 44 pages. Submitted to J. Fluid Mech.

A comparison of several commonly used turbulence models (including the K- ϵ model and two second-order closures) is made for the test problem of homogeneous turbulent shear flow in a rotating frame. The time evolution of the turbulent kinetic energy and dissipation rate is calculated for a variety of models and comparisons are made with previously published experiments and numerical simulations. Particular emphasis is placed on examining the ability of each model to accurately predict equilibrium states for a range of the parameter Ω/S (the ratio of the rotation rate to the shear rate). It is found that none of the commonly used second-order closure models yield substantially improved predictions for the time evolution of the turbulent kinetic energy and dissipation rate over the somewhat defective results obtained from the simpler K- ϵ model for the turbulent flow regime. There is also a problem with the equilibrium states predicted by the various models. For example, the K- ϵ model erroneously yields equilibrium states that are independent of Ω/S while the Launder, Reece, and Rodi model predicts a flow relaminarization when $\Omega/S > 0.39$ – a result which is contrary to numerical simulations and linear spectral analyses which indicate flow instability for at least the range $0 \leq \Omega/S \leq 0.5$. The physical implications of the results obtained from the various turbulence models considered herein are discussed in detail along with proposals to remedy the deficiencies based on a dynamical systems approach.

Kojima, Fumio: *Parameter estimation for boundary value problems by integral equations of the second kind*. ICASE Report No. 88-28, April 28, 1988, 40 pages. Submitted to Control Theory Adv. Tech.

This paper is concerned with the parameter estimation for boundary integral equations of the second kind. The parameter estimation technique by using the spline collocation method is proposed. Based on the compactness assumption imposed on the parameter space, the convergence analysis for the numerical method of parameter estimation is discussed. The results obtained here are applied to a boundary parameter estimation for 2-D elliptic systems.

Nicol, David M.: *Parallel discrete-event simulation of FCFS stochastic queueing networks*. ICASE Report No. 88-29, May 24, 1988, 22 pages. Submitted to SIGPLAN PPEALS Symposium.

Physical systems are inherently parallel; intuition suggests that simulations of these systems may be amenable to parallel execution. The parallel execution of a discrete-event simulation requires careful synchronization of processes in order to ensure the execution's correctness; this synchronization can degrade performance. Largely negative results were recently reported in a study which used a well-known synchronization method on queueing network simulations. In this paper, we discuss a synchronization method, appointments, which has proven itself to be effective on simulations of FCFS queueing networks. The key concept behind appointments is the provision of lookahead. Lookahead is a prediction on a processor's future behavior, based on an analysis of the processor's simulation state. We show how lookahead can be computed for FCFS queueing network simulations, give performance data that demonstrates the method's effectiveness under moderate to heavy loads, and discuss performance trade-offs between the quality of lookahead, and the cost of computing lookahead.

Turkel, Eli: *Accuracy versus convergence rates for a three dimensional multistage Euler code*. ICASE Report No. 88-30, May 3, 1988, 20 pages. Submitted to 16th ICAS Congress, Jerusalem.

Using a central difference scheme, it is necessary to add an artificial viscosity in order to reach a steady state. This viscosity usually consists of a linear fourth difference to eliminate odd-even oscillations and a non linear second difference to suppress oscillations in the neighborhood of steep gradients. There are free constants in these differences. As one increases the artificial viscosity, the high modes are dissipated more and the scheme converges more rapidly. However, this higher level of viscosity smooths the shocks and eliminates other features of the flow. Thus, there is a conflict between the requirements of accuracy and efficiency. Examples are presented for a variety of three-dimensional inviscid solutions over isolated wings.

Protzel, Peter W.: *Automatically generated acceptance test: A software reliability experiment*. ICASE Report No. 88-31, May 5, 1988, 21 pages. Submitted to the Proc. of the Second Workshop on Software Testing, Verification, and Analysis, Banff, Alberta, Canada, 1988.

This study presents results of a software reliability experiment that investigates the feasibility of a new error detection method. The method can be used as an acceptance test and is solely based on empirical data about the behavior of internal states of a program. The experimental design uses the existing environment of a multi-version experiment previously conducted at the NASA Langley Research Center, in which the "launch interceptor" problem is used as a model problem. This allows the controlled experimental investigation of versions with well-known single and multiple faults, and the availability of an oracle permits the determination of the error detection performance of the test. Fault-interaction phenomena are observed that have an amplifying effect on the number of error occurrences. Preliminary results indicate that all faults examined so far are detected by the acceptance test. This shows promise for further investigations, and for the employment of this test method in other applications.

Arnone, A. and R. C. Swanson: *A Navier-Stokes solver for cascade flows*. ICASE Report No. 88-32, July 7, 1988, 27 pages. Submitted to J. of Engineering for Gas Turbines and Power.

A computer code for solving the Reynolds averaged full Navier-Stokes equations has been developed and applied using sheared H-type grids. The Baldwin-Lomax eddy-viscosity model is used for turbulence closure. The integration in time is based on an explicit four-stage Runge-Kutta scheme. Local time stepping, variable coefficient implicit residual smoothing, and a full multigrid method have been implemented to accelerate steady state calculations. Comparisons with experimental data show that the code is an accurate viscous solver and can give very good blade-to-blade predictions for engineering applications in less than 100 multigrid cycles on the finest mesh.

Jackson, T. L. and C. E. Grosch: *Spatial stability of a compressible mixing layer*. ICASE Report No. 88-33, June 1, 1988, 54 pages. Submitted to J. Fluid Mech.

We present the results of a study of the inviscid spatial stability of a parallel compressible mixing layer. The parameters of this study are the Mach number of the moving stream, the ratio of the temperature of the stationary stream to that of the moving stream, the frequency and the direction of propagation of the disturbance wave. Stability characteristics of the flow as a function of these parameters are given. It is shown that if the Mach number exceeds a critical value there are always two groups of unstable waves. One of these groups is fast with phase speeds greater than $1/2$, and the other is slow with phase speeds less than $1/2$. Phase speeds for the neutral and unstable modes have the same general behavior as the two dimensional modes but with higher growth rates over some range of propagation direction. Finally, we have found for sufficiently large Mach numbers a group of very low frequency unstable modes. These modes have very low phase speeds but large growth rates.

Speziale, Charles G. and Nessim Mac Giolla Mhuiris: *Scaling laws for homogeneous turbulent shear flows in a rotating frame*. ICASE Report No. 88-34, June 2, 1988, 25 pages. Submitted to the Physics of Fluids.

The scaling properties of plane homogeneous turbulent shear flows in a rotating frame are examined mathematically by a direct analysis of the Navier-Stokes equations. It is proven that two such shear flows are dynamically similar if and only if their initial dimensionless energy spectrum $E^*(k^*, 0)$, initial dimensionless shear rate SK_0/ϵ_0 , initial Reynolds number $K_0^2/\nu\epsilon_0$, and the ratio of the rotation rate to the shear rate Ω/S are identical. Consequently, if universal equilibrium states exist, at high Reynolds numbers, they will only depend on the single parameter Ω/S . The commonly assumed dependence of such equilibrium states on Ω/S through the Richardson number $Ri = -2(\Omega/S)(1 - 2\Omega/S)$ is proven to be inconsistent with the full Navier-Stokes equations and to constitute no more than a weak approximation. To be more specific, Richardson number similarity is shown to only rigorously apply to certain low-order truncations of the Navier-Stokes equations (i.e., to certain second-order closure models) wherein closure is achieved at the second-moment level by assuming that the higher-order moments are a small perturbation of their isotropic

states. The physical dependence of rotating turbulent shear flows on Ω/S is discussed in detail along with the implications for turbulence modeling.

Rosen, I. G.: *Optimal discrete-time LQR problems for parabolic systems with unbounded input - approximation and convergence*. ICASE Report No. 88-35, June 7, 1988, 30 pages. Submitted to J. Control-Theory and Advanced Technology.

An abstract approximation and convergence theory for the closed-loop solution of discrete-time linear-quadratic regulator problems for parabolic systems with unbounded input is developed. Under relatively mild stabilizability and detectability assumptions, functional analytic, operator theoretic techniques are used to demonstrate the norm convergence of Galerkin-based approximations to the optimal feedback control gains. The application of the general theory to a class of abstract boundary control systems is considered. Two examples, one involving the Neumann boundary control of a one dimensional heat equation, and the other, the vibration control of a cantilevered viscoelastic beam via shear input at the free end, are discussed.

Bernstein, Dennis S. and I. Gary Rosen: *Finite-dimensional approximation for optimal fixed-order compensation of distributed parameter systems*. ICASE Report No. 88-36, June 7, 1988, 23 pages. Submitted to Optimal Control - Application and Methods.

In controlling distributed parameter systems it is often desirable to obtain low-order, finite-dimensional controllers in order to minimize real-time computational requirements. Standard approaches to this problem employ model/controller reduction techniques in conjunction with LQG theory. In this paper we consider the finite-dimensional approximation of the infinite-dimensional Bernstein/Hyland optimal projection theory. Our approach yields fixed-finite-order controllers which are optimal with respect to high-order, approximating, finite-dimensional plant models. We illustrate the technique by computing a sequence of first-order controllers for one-dimensional, single-input/single-output, parabolic (heat/diffusion) and hereditary systems using spline-based, Ritz-Galerkin, finite element approximation. Our numerical studies indicate convergence of the feedback gains with less than 2% performance degradation over full-order LQG controllers for the parabolic system and 10

Cai, Wei, David Gottlieb, and Chi-Wang Shu: *Non-oscillatory spectral Fourier methods for shock wave calculations*. ICASE Report No. 88-37, June 9, 1988, 31 pages. Submitted to Math. Comp.

In this paper, we present a non-oscillatory spectral Fourier method for the solution of hyperbolic partial differential equations. The method is based on adding a nonsmooth function to the trigonometric polynomials which are the usual basis functions for the Fourier method. The high accuracy away from the shock is enhanced by using filters. Numerical results confirm that no oscillations develop in the solution. Also, the accuracy of the spectral solution of the inviscid Burgers equation is shown to be higher than a fixed order.

Banks, H. T., Simeon Reich, I. G. Rosen: *Galerkin approximation for inverse problems for nonautonomous nonlinear distributed systems*. ICASE Report No. 88-38, June 10, 1988, 21 pages. Submitted to Applied Mathematics and Optimization.

We develop an abstract framework and convergence theory for Galerkin approximation for inverse problems involving the identification of nonautonomous nonlinear distributed parameter systems. We provide a set of relatively easily verified conditions which are sufficient to guarantee the existence of optimal solutions and their approximation by a sequence of solutions to a sequence of approximating finite dimensional identification problems. Our approach is based upon the theory of monotone operators in Banach spaces and is applicable to a reasonably broad class of nonlinear distributed systems. Operator theoretic and variational techniques are used to establish a fundamental convergence result. An example involving evolution systems with dynamics described by nonstationary quasi-linear elliptic operators along with some applications are presented and discussed.

Tal-Ezer, Hillel: *High degree interpolation polynomial in Newton form*. ICASE Report No. 88-39, June 13, 1988, 23 pages. Submitted to SIAM J. Sci. Comput.

Polynomial interpolation is an essential subject in numerical analysis. Dealing with a real interval, it is well-known that even if $f(x)$ is an analytic function, interpolating at equally spaced points can diverge [Davi75]. On the other hand, interpolating at the zeroes of the corresponding Chebyshev polynomial will converge. Using the Newton formula, this result of convergence is true only on the theoretical level. It is shown that the algorithm which computes the divided differences is numerically stable only if: 1.) the interpolating points are arranged in a certain order, 2.) the size of the interval is 4.

Mavriplis, Dimitri J.: *Accurate multigrid solution of the Euler equations on unstructured and adaptive meshes*. ICASE Report No. 88-40, June 16, 1988, 31 pages. Submitted to AIAA J.

A method for accurately solving inviscid compressible flow in the subcritical and supercritical regimes about complex configurations is presented. The method is based on the use of unstructured triangular meshes in two dimensions, and special emphasis is placed on the accuracy and efficiency of the solutions. High accuracy is achieved by careful scaling of the artificial dissipation terms, and by reformulating the inner and outer boundary conditions for both the convective and dissipative operators. An adaptive grid refinement strategy is presented which enhances the solution accuracy for complex flows. When coupled with an unstructured multigrid algorithm, this method is shown to produce an efficient solver for flows about arbitrary configurations.

Tadmor, Eitan: *Semi-discrete approximations to nonlinear systems of conservation laws; consistency and L^∞ -stability imply convergence*. ICASE Report No. 88-41, July 7, 1988, 62 pages. Submitted to Math. Comp.

We develop a convergence theory for semi-discrete approximations to nonlinear systems of conservation laws. We show, by a series of scalar counterexamples, that consistency with the conservation law alone does not guarantee convergence. Instead, we introduce a notion of consistency which takes into account both the conservation law and its augmenting entropy condition. In this context, we conclude that consistency and L^∞ -stability guarantee for a "relevant" class of admissible entropy functions, that their entropy production rate belong to a compact subset of $H_{loc}^{-1}(x, t)$. One can use now compensated compactness arguments in order to turn this conclusion into a convergence proof. The current state of the art for these arguments includes the scalar and a wide class of 2×2 systems of conservation laws.

We study the general framework of the vanishing viscosity method as an effective way to meet our consistency and L^∞ -stability requirements. We show how this method is utilized to enforce consistency and L^∞ -stability for scalar conservation laws. In this context, we prove under the appropriate assumptions (L^∞ -bounds), the convergence of finite-difference approximations (e.g., the high-resolution TVD and UNO methods), finite-element approximations (e.g., the Streamline-Diffusion methods) and spectral and pseudospectral approximations (e.g., the Spectral Viscosity methods).

Duck, Peter W. and Philip Hall: *Nonaxisymmetric viscous lower branch modes in axisymmetric supersonic flows*. ICASE Report No. 88-42, July 27, 1988, 22 pages. Submitted to J. Fluid Mech.

In a previous paper, we have considered the weakly nonlinear interaction of a pair of axisymmetric lower branch Tollmien-Schlichting instabilities in cylindrical supersonic flows. Here the possibility that nonaxisymmetric modes might also exist is investigated. In fact it is found that such modes do exist and, on the basis of linear theory, it appears that these modes are the most important. The nonaxisymmetric modes are found to exist for flows around cylinders with nondimensional radius a less than some critical value a_c . This critical value a_c is found to increase monotonically with the azimuthal wavenumber n of the disturbance and it is found that unstable modes always occur in pairs. We show that in general, instability in the form of lower branch Tollmien-Schlichting waves will occur first for nonaxisymmetric modes and that in the unstable regime, the largest growth rates correspond to the latter modes.

Bassom, Andrew P. and Philip Hall: *On the generation of mean flows by the interaction of Görtler vortices and Tollmien-Schlichting waves in curved channel flows*. ICASE Report No. 88-43, July 29, 1988, 40 pages. Submitted to Studies in Applied Maths.

There are many fluid flows where the onset of transition can be caused by different instability mechanisms which compete in the nonlinear regime. Here the interaction of a centrifugal instability mechanism with the viscous mechanism which causes Tollmien-Schlichting waves is discussed. The interaction between these modes can be strong enough to drive the mean state; here the interaction is investigated in the context of curved channel flows so as to avoid difficulties associated with boundary layer growth. Essentially it is found that the mean state adjusts itself so that any modes present are neutrally stable even at finite amplitude. In the first instance, the mean state driven by a vortex of short wavelength in the absence of a Tollmien-Schlichting wave is considered. It is shown that for a given channel curvature and vortex wavelength there is an upper limit

to the mass flow rate which the channel can support as the pressure gradient is increased. When Tollmien-Schlichting waves are present then the nonlinear differential equation to determine the mean state is modified. At sufficiently high Tollmien-Schlichting amplitudes it is found that the vortex flows are destroyed, but there is a range of amplitudes where a fully nonlinear mixed vortex-wave state exists and indeed drives a mean state having little similarity with the flow which occurs without the instability modes. The vortex and Tollmien-Schlichting wave structure in the nonlinear regime has viscous wall layers and internal shear layers; the thickness of the internal layers is found to be a function of the Tollmien-Schlichting wave amplitude.

Morkovin, Mark V.: *Recent insights into instability and transition to turbulence in open-flow systems*. ICASE Report No. 88-44, August 11, 1988, 83 pages. Submitted to Proc. 1st National Congress on Fluid Dynamics.

Roads to turbulence in open-flow shear layers are interpreted as sequences of often competing instabilities. These correspond to primary and higher-order restructurings of vorticity distributions which culminate in convected spatial disorder (with some spatial coherence on the scale of the shear layer) traditionally called turbulence. Attempts are made to interpret these phenomena in terms of concepts of convective and global instabilities on one hand, and of chaos and strange attractors on the other. The first is fruitful, and together with a review of mechanisms of receptivity provides a unifying approach to understanding and estimating transition to turbulence. In contrast, current evidence indicates that concepts of chaos are unlikely to help in predicting transition in open-flow systems. Furthermore, a distinct tion should apparently be made between temporal chaos and the convected spatial disorder of turbulence past Reynolds numbers where boundary layers and separated shear layers are formed.

Bennett, J., P. Hall, and F. T. Smith: *The strong nonlinear interaction of Tollmien-Schlichting waves and Taylor-Görtler vortices in curved channel flow*. ICASE Report No. 88-45, August 17, 1988, 34 pages. Submitted to Journal of Fluid Mechanics.

Viscous fluid flows with curved streamlines can support both centrifugal and viscous travelling wave instabilities. Here the interaction of these instabilities in the context of the fully developed flow in a curved channel is discussed. The viscous (Tollmien-Schlichting) instability is described asymptotically at high Reynolds numbers and it is found that it can induce a Taylor-Görtler flow even at extremely small amplitudes. In this interaction, the Tollmien-Schlichting wave can drive a vortex state with wavelength either comparable with the channel width or the wavelength of lower branch viscous modes. The nonlinear equations which describe these interactions are solved for nonlinear equilibrium states.

Hall, P. and F. T. Smith: *Nonlinear Tollmien-Schlichting/vortex interaction in boundary layers*. ICASE Report No. 88-46, August 17, 1988, 36 pages. Submitted to Journal of Fluid Mechanics.

The nonlinear interaction between two oblique three-dimensional Tollmien-Schlichting (TS) waves and their induced streamwise-vortex flow is considered theoretically for an

incompressible boundary layer. The same theory applies to the de-stabilization of an incident vortex motion by sub-harmonic TS waves, followed by interaction. The scales and flow structure involved are addressed for high Reynolds numbers. The nonlinear interaction is powerful, starting at quite low amplitudes with a triple-deck structure for the TS waves but a large-scale structure for the induced vortex, after which strong nonlinear amplification occurs. This includes nonparallel-flow effects. The nonlinear interaction is governed by a partial-differential system for the vortex flow coupled with an ordinary-differential one for the TS pressure. The solution properties found sometimes produce a break-up within a finite distance and sometimes further downstream, depending on the input amplitudes upstream and on the wave angles, and that then leads on to the second stages of interaction associated with higher amplitudes, the main second stages giving either long-scale phenomena significantly affected by nonparallelism or shorter quasi-parallel ones governed by the full nonlinear triple-deck response. Qualitative comparisons with experiments are noted.

Mavriplis, Dimitri J.: *Adaptive mesh generation for viscous flows using Delaunay triangulation*. ICASE Report No. 88-47, August 17, 1988, 15 pages. Submitted to the Proc. of the Second International Conference on Numerical Grid Generation in Computational Fluid Dynamics, Pineridge Press.

A method for generating an unstructured triangular mesh in two dimensions, suitable for computing high Reynolds number flows over arbitrary configurations is presented. The method is based on a Delaunay triangulation, which is performed in a locally stretched space, in order to obtain very high aspect ratio triangles in the boundary layer and wake regions. It is shown how the method can be coupled with an unstructured Navier-Stokes solver to produce a solution adaptive mesh generation procedure for viscous flows.

Gibson, J. S. and A. Adamian: *Approximation theory for LQG optimal control of flexible structures*. ICASE Report No. 88-48, August 26, 1988, 120 pages. Submitted to SIAM J. Control Optim.

This paper presents approximation theory for the linear-quadratic-Gaussian optimal control problem for flexible structures whose distributed models have bounded input and output operators. The main purpose of the theory is to guide the design of finite dimensional compensators that approximate closely the optimal compensator. The main problem lies in the solution to an infinite dimensional Riccati operator equation. The approximation scheme in the paper approximates the infinite dimensional LQG problem with a sequence of finite dimensional LQG problems defined for a sequence of finite dimensional, usually finite element or modal, approximations of the distributed model of the structure. Two Riccati matrix equations determine the solution to each approximating problem.

The finite dimensional equations for numerical approximation are developed, including formulas for converting matrix control and estimator gains to their functional representation to allow comparison of gains based on different orders of approximation. Convergence of the approximating control and estimator gains and of the corresponding finite dimensional compensators is studied. Also, convergence and stability of the closed-loop systems produced with the finite dimensional compensators are discussed. The convergence theory is based on the convergence of the solutions of the finite dimensional Riccati equations to

the solutions of the infinite dimensional Riccati equations. A numerical example with a flexible beam, a rotating rigid body, and a lumped mass is given.

Rosen, I. G.: *Convergence of Galerkin approximations for operator Riccati equations - A nonlinear evolution equation approach*. ICASE Report No. 88-49, August 29, 1988, 29 pages.

We develop an approximation and convergence theory for Galerkin approximations to infinite dimensional operator Riccati differential equations formulated in the space of Hilbert-Schmidt operators on a separable Hilbert space. We treat the Riccati equation as a nonlinear evolution equation with dynamics described by a nonlinear monotone perturbation of a strongly coercive linear operator. We prove a generic approximation result for quasi-autonomous nonlinear evolution systems involving accretive operators which we then use to demonstrate the Hilbert-Schmidt norm convergence of Galerkin approximations to the solution of the Riccati equation. We illustrate the application of our results in the context of a linear quadratic optimal control problem for a one dimensional heat equation.

Ta'asan, Shlomo: *Multigrid methods for locating singularities in bifurcation problems*. ICASE Report No. 88-50, September 1, 1988, 21 pages. Submitted to SIAM J. Stat. Sci. Comp.

This paper deals with multigrid methods for locating singular points for nonlinear equations, such as limit points and bifurcation points (perfect or imperfect) and is restricted to the self adjoint case. A minimization problem that defines singular points is formulated. It treats uniformly limit points and bifurcation points unlike other methods which are designed to solve for one of the two. So it is particularly useful when the type of singularity, or even its existence are not known in advance. Efficient multigrid methods for locating singular points based on the minimization problem are described. They solve the problems to the level of discretization errors in just a few work units (about 10 or less), where a work unit is the work involved in one local relaxation on the finest grid.

Nessyahu, Haim and Eitan Tadmor: *Non-oscillatory central differencing for hyperbolic conservation laws*. ICASE Report No. 88-51, September 2, 1988, 52 pages. Submitted to J. Comp. Phys.

Many of the recently developed high-resolution schemes for hyperbolic conservation laws are based on upwind differencing. The building block of these schemes is the averaging of an appropriate Godunov solver; its time consuming part involves the field-by-field decomposition which is required in order to identify the "direction of the wind." Instead, we propose to use as a building block the more robust Lax-Friedrichs (LxF) solver. The main advantage is simplicity: no Riemann problems are solved and hence field-by-field decompositions are avoided. The main disadvantage is the excessive numerical viscosity typical to the LxF solver. We compensate for it by using high-resolution MUSCL-type interpolants. Numerical experiments show that the quality of the results obtained by such convenient central differencing is comparable with those of the upwind schemes.

Keyes, David: *Domain decomposition methods for the parallel computation of reacting flows*. ICASE Report No. 88-52, September 14, 1988, 25 pages. Submitted to the Minnesota Supercomputer Institute's Workshop on Practical Iterative Methods for Large-Scale Problems.

Domain decomposition is a natural route to parallel computing for partial differential equation solvers. In this procedure, subdomains of which the original domain of definition is comprised are assigned to independent processors at the price of periodic coordination between processors to compute global parameters and maintain the requisite degree of continuity of the solution at the subdomain interfaces. In the domain-decomposed solution of steady multidimensional systems of PDEs by finite difference methods using a pseudo-transient version of Newton iteration, the only portion of the computation which generally stands in the way of efficient parallelization is the solution of the large, sparse linear systems arising at each Newton step. For some Jacobian matrices drawn from an actual two-dimensional reacting flow problem, we make comparisons between relaxation-based linear solvers and also preconditioned iterative methods of Conjugate Gradient and Chebyshev type, focusing attention on both iteration count and global inner product count. The generalized minimum residual method with block-ILU preconditioning is judged the best serial method among these considered, and parallel numerical experiments on the Encore Multimax demonstrate for it approximately 10-fold speedup on 16 processors. The three special features of reacting flow models in relation to these linear systems are: the possibly large number of degrees of freedom per gridpoint, the dominance of dense intra-point source-term coupling over inter-point convective-diffusive coupling throughout significant portions of the flow-field, and strong nonlinearities which restrict the time-step to small values (independent of linear algebraic considerations) throughout significant portions of the iteration history. Though these features are exploited to advantage herein, many aspects of the paper are applicable to the modeling of general convective-diffusive systems.

Turkel, Eli: *Improving the accuracy of central difference schemes.*, ICASE Report No. 88-53, September 7, 1988, 14 pages. Submitted to the 11th International Conference on Numerical Methods and Fluid Dynamics.

Central difference approximations to the fluid dynamic equations require an artificial viscosity in order to converge to a steady state. This artificial viscosity serves two purposes. One is to suppress high frequency noise which is not damped by the central differences. The second purpose is to introduce an entropy-like condition so that shocks can be captured. These viscosities need a coefficient to measure the amount of viscosity to be added. In the standard scheme, a scalar coefficient is used based on the spectral radius of the Jacobian of the convective flux. However, this can add too much viscosity to the slower waves. Hence, we suggest using a matrix viscosity. This gives an appropriate viscosity for each wave component. With this matrix valued coefficient, the central difference scheme becomes closer to upwind biased methods.

Augenbaum, Jeffrey M.: *An adaptive pseudospectral method for discontinuous problems*. ICASE Report No. 88-54, September 12, 1988, 33 pages. To appear in *Applied Numerical Mathematics*.

In this paper, we study the accuracy of adaptively chosen, mapped polynomial approximations for functions with steep gradients or discontinuities. We show that, for steep gradient functions, one can obtain spectral accuracy in the original coordinate system by using polynomial approximations in a transformed coordinate system with substantially fewer collocation points than are necessary using polynomial expansion directly in the original, physical, coordinate system. We also show that one can avoid the usual Gibbs oscillation, associated with steep gradient solutions of hyperbolic pde's, by approximation in suitably chosen coordinate systems. Continuous, high gradient, solutions are computed with spectral accuracy (as measured in the physical coordinate system). Discontinuous solutions associated with nonlinear hyperbolic equations can be accurately computed by using an artificial viscosity chosen to smooth out the solution in the mapped, computational, domain. Thus, we can effectively resolve shocks on a scale that is subgrid to the resolution available with collocation only in the physical domain. Examples with Fourier and Chebyshev collocation are given.

ICASE INTERIM REPORTS

Middleton, David, Tom Crockett, and Sherry Tomboulia: *Programming the Navier-Stokes computer: An abstract machine model and a visual editor*. ICASE Interim Report No. 5, August 4, 1988, 30 pages.

The Navier-Stokes Computer is a parallel computer designed to solve Computational Fluid Dynamics problems. Each processor contains several floating point units which can be configured under program control to implement a vector pipeline with several inputs and outputs. Since the development of an effective compiler for this computer appears to be very difficult, machine level programming seems necessary and we have studied support tools for this process. These support tools are organized into a graphical program editor.

A programming process is described by which appropriate computations may be efficiently implemented on the Navier-Stokes computer. The graphical editor would support this programming process, verifying various programmer choices for correctness and deducing values such as pipeline delays and network configurations. Step by step details are provided and demonstrated with two example programs.

We also describe an abstract reconfigurable vector processor in place of the actual processor used in the Navier-Stokes computer. This abstract node provides a firm and simple definition around which the editor and the programming activity can be designed. It is a subset of the actual node, displaying the important facilities of an actual node while hiding various implementation details from the programmer. Because of the intended applications, aspects of multiprogramming such as synchronization and communication have been ignored; it is expected that simple program barriers will suffice. Designing the abstract node to match the machine facilities used during the programming process provides some early feedback on features provided in the actual node processors.

ICASE COLLOQUIUM

April 1 - September 30, 1988

Name/Affiliation/Title	Date
Professor Frederic Bisshopp, Brown University "The Effect of Interpolation Errors on Shock Capture/Chase Algorithms"	April 5
Dr. James Keeler, Stanford University "Information Capacity for Patterns and Sequences in Kanerva and Hopfield-Type Neural Networks"	April 15
Mr. Pui-kuen Yeung, Cornell University "Lagrangian Turbulence Statistics from Direct Simulations"	April 19
Professor J. N. Reddy, Virginia Polytechnic Institute and State University "On Computational Models of Fluid Flow and Composite Laminates"	April 20
Mr. Yuh-Roung Ou, University of Southern California "Analysis of Regularized Navier-Stokes Equations"	April 22
Mr. S. Balachandar, Brown University "Particle Coagulation in Homogeneous Turbulence"	April 26
Professor Ronald Rivlin, Lehigh University "How Rational is Rational Mechanics?"	April 27
Mr. Courtenay Vaughan, University of Virginia "The SSOR Preconditioned Conjugate Gradient Method on Parallel Computers"	April 29
Dr. Mark Morkovin "Absolute Instability and its Implications for Research in Open Flow Systems"	May 17

Name/Affiliation/Title	Date
Mr. Sutanu Sarkar, Cornell University "Turbulent Flow of Fiber Suspensions"	May 26
Dr. Jay Boris, U. S. Naval Research Laboratory "New Directions in CFD Using Montone Algorithms"	June 2
Dr. Elaine Oran, U. S. Naval Research Laboratory "Numerical Simulations of Unsteady Shear Layers"	June 3
Professor Einar Ronquist, Massachusetts Institute of Technology "Optimal Spectral Element Methods for the Unsteady Three-Dimensional Incompressible Navier-Stokes Equations"	June 10
Professor David Gottlieb, Brown University and ICASE "Non-Oscillatory Spectral Methods"	June 16
Dr. David Keyes, Yale University "Domain Decomposition for Nonsymmetric Systems of Equations: Examples from Computational Fluid Dynamics"	July 6
Professor Steve Elliott, University of Southampton, England "The Active Control of Enclosed Sound Fields"	July 7
Professor Robert MacCormack, Stanford University "Difficulties in Developing Numerical Methods for 3D Compressible Flow"	July 8
Professor Eitan Tadmor, Tel-Aviv University and ICASE "Consistency and Stability Imply the Convergence of Nonlinear Approximations to Systems of Conservation Laws"	August 16
Professor Victor Yakhot, Princeton University "Theoretical Justification of the Renormalization Group Theory of Turbulence"	August 23
Professor Philip Hall, University of Exeter, England "Centrifugal, Viscous and Inviscid Modes of Instability of Hypersonic Boundary Layers"	September 12

Name/Affiliation/Title	Date
Professor David Silvester, The University of Manchester Institute of Science and Technology "The Stabilisation of Low Order Mixed Finite Element Methods for Incompressible Flow"	September 15
Professor K. R. Sreenivasan, Yale University "Geometry and Dynamics of Fully Turbulent Flows"	September 19
Professor Stanley Osher, University of California, Los Angeles "High-Order Accurate Essentially Non-Oscillatory Methods for Front and Shock Capturing"	September 28

ICASE SUMMER ACTIVITIES

The summer program for 1988 included the following visitors:

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Saul S. Abarbanel Tel-Aviv University	7/25 - 10/7	Computational Fluid Dynamics
Loyce M. Adams University of Washington	8/15 - 8/19	Numerical Methods for Parallel Computing Systems
H. Thomas Banks Brown University	6/3 - 6/15	Control Theory
Shahid H. Bokhari Pakistan University of Engineering and Technology	6/7 - 8/12	Parallel and Distributed Computing
Dennis W. Brewer University of Arkansas	6/12 - 6/17 8/1 - 8/19	Control Theory
Henri Cabannes Universite Pierre et Marie Curie, France	7/4 - 7/8	Discrete Models of Boltzmann Equation
Stephen J. Cowley Imperial College, England	7/25 - 8/26	Computational Fluid Dynamics
Michel Deville Universite Catholique de Louvain, Belgium	8/8 - 9/9	Preconditioned Iterative Spectral Methods
Wai Sun Don Brown University	6/6 - 6/17	Computational Fluid Dynamics
Peter W. Duck University of Manchester, England	7/11 - 8/26	Numerical Solution of Unsteady Boundary Layer Equation

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Stephen J. Elliott Institute of Sound and Vibration Research, University of Southampton England	6/27 - 8/19	Control Theory
J. Steven Gibson University of California, LA	6/6 - 6/17	Control Theory
David Gottlieb Brown University	6/6 - 6/17 7/11 - 7/15 8/15 - 8/26	Numerical Methods for PDE's
Chester E. Grosch Old Dominion University	6/1 - 8/31	Computational Fluid Dynamics
Philip Hall Exeter University, England	6/6 - 6/10 7/11 - 9/30	Computational Fluid Dynamics
Amiram Harten Tel-Aviv University, Israel	6/20 - 8/26	Numerical Methods for PDE's
Thorwald Herbert Ohio State University	6/6 - 6/10	Fluid Dynamics
Kazufumi Ito Brown University	6/6 - 6/17	Control Theory
Mark Jones Duke University	8/15 - 8/19	Algorithms for Parallel Systems
Harry F. Jordan University of Colorado	6/13 - 6/17	Parallel Processing Systems
Ashwani K. Kapila Rensselaer Polytechnic Institute	7/18 - 7/29	Mathematical Aspects of Combustion Processes
David E. Keyes Yale University	6/20 - 7/8	Parallel Methods Appropriate for Combustion Problems
David Kopriva Florida State University	6/20 - 7/1	Spectral Methods for Problems in Fluid Dynamics

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Randall J. LeVeque University of Washington	8/15 - 8/19	Numerical Methods for PDE's
Robert W. MacCormack Stanford University	6/27 - 7/8	Numerical Methods for Hypersonic Flows
Yvon Maday Brown University	6/20 - 7/29	Analysis of Spectral Methods
Lionel Marraffa ONERA, France	5/30 - 6/10	Hypersonic Flow Modelling and Computations
Piyush Mehrotra Purdue University	6/6 - 8/12	Programming Languages for Multiprocessor Systems
Ravi Mirchandaney Yale University	5/24 - 5/27	Analysis of Automated Parallel Problem Mapping Strategies
B. Muller DFVLR, Institute for Theoretical Fluid Mechanics, Germany	7/4 - 7/8	Computational Methods for Hypersonics
David M. Nicol College of William and Mary	7/18 - 8/12	Techniques for Mapping Algorithms onto Parallel Computing Systems
Tobias Orloff University of Minnesota	9/1 - 2 years	Hi-Performance Graphics
Stanley J. Osher University of California, LA	9/28 - 9/30	Numerical Techniques for Problems in Fluid Dynamics
Koichi Oshima The Institute of Space and Astronautical Science, Japan	7/4 - 7/8	Vortex Interaction Problem Based on Navier-Stokes Equations
Demetrius Papageorgiou City College of New York	7/4 - 8/26	Computational Fluid Dynamics
Merrell L. Patrick Duke University	5/1 - 8/20	Algorithms for Parallel Array Computers

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Ugo Piomelli University of Maryland	7/18 - 8/12	Large Eddy Simulation
Terrence W. Pratt University of Virginia	6/21 - 6/23	Programming Languages
Daniel A. Reed University of Illinois	8/22 - 8/26	Performance of Parallel and Distributed Systems
Helen Reed Arizon State University	7/31 - 8/5	Computational Fluid Dynamics Related to Studies of Transition
Philip L. Roe Cranfield Institute of Technology England	7/4 - 7/15	Computational Fluid Dynamics
I. Gary Rosen University of Southern California	6/6 - 6/17	Numerical Methods for Problems in Control Systems
Philippe Rostand Institut National de Recherche, France	7/4 - 9/23	Numerical Methods Relating to Hypersonics Especially Real Gas Effects and Turbulence
Joel H. Saltz Yale University	5/19 - 5/27	Analysis of Automated Parallel Problem Mapping Strategies
Paul E. Saylor University of Illinois	6/13 - 6/17	Iterative Parallel Methods for Linear Systems
Jeffrey S. Scroggs University of Illinois	7/4 - 2 years	Domain Decomposition Asymptotic Methods for PDE's
Sharon O. Seddoui University of Exeter, England	6/1 - 2 years	Instability Transition in Boundary Layer Flows
Scott A. Sibio Princeton University	6/6 - 7/22	Shock Fitting Techniques using Triangular Grids

<u>NAME/AFFILIATION</u>	<u>DATE OF VISIT</u>	<u>AREA OF INTEREST</u>
Frank T. Smith University College London, England	7/4 - 7/22 9/12 - 9/30	Theory and Computation of Boundary Layer Unstabilities and Transition
Shlomo Ta'asan The Weizmann Institute of Science	7/18 - 9/16	Multi-Grid Methods for PDE's
Eitan Tadmor Tel-Aviv University, Israel	6/27 - 9/30	Numerical Methods for PDE's
Hillel Tal-Ezer Brown University	8/1 - 9/30	Spectral Methods for PDE's
Lu Ting Northwestern University, Illinois	6/20 - 7/1	Fluid Mechanics
Eli Turkel Tel-Aviv University, Israel	6/20 - 8/26	Computational Fluid Dynamics
Hervé Vandeven Universite Pierre et Marie Curie, France	7/25 - 8/5	Analysis of Spectral Methods
Bram van Leer University of Michigan	6/27 - 7/15	Computational Fluid Dynamics
Yun Wang Brown University	5/31 - 6/10	Control Theory

OTHER ACTIVITIES

The 11th International Conference on Numerical Methods in Fluid Dynamics co-sponsored by ICASE and NASA Langley Research Center was held June 27-July 1 at the College of William and Mary, Williamsburg, Virginia. Two hundred and fifty people from twelve countries attended this meeting. Approximately 70 papers were presented on Computational Fluid Dynamics including the areas of algorithm development, plasma dynamics, parallel processing, hypersonic flows, transition and turbulence, and reacting flows. In addition, 35 poster paper sessions were presented. Invited speakers and their topics are listed below.

K. V. Brushlinsky, Keldysh Institute of Applied Mathematics, USSR:
"Computational Models in Plasma Dynamics"

T. Hoshino, University of Tsukuba, Japan:
"Parallel Computers and Parallel Computing in Scientific Simulations"

M. Y. Hussaini, ICASE, USA:
"Computational Fluid Dynamics - A Personal View"

A. Kumar, NASA Langley Research Center, USA:
"CFD for Hypersonic Airbreathing Aircraft"

P. Roe, Cranfield Institute of Technology, England:
"A Review of Upwind Differencing Techniques"

K. Stuben, Gesellschaft fur Mathematik and Datenverarbeitung MBH, Germany:
"Parallel Multigrid for the Incompressible Navier-Stokes Equations on General 2D-Domains"

R. Temam, Universite de Paris-Sud, France:
"Dynamical Systems Turbulence and the Numerical Solution of Navier-Stokes Equations"

A volume of the proceedings from this conference will be published by Springer-Verlag in the near future.

ICASE STAFF

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